Defense Technical Information Center Compilation Part Notice

ADP012913

TITLE: Electronic Structure of Stacked Self-Organized InAs/GaAs Quantum Dots

DISTRIBUTION: Approved for public release, distribution unlimited
Availability: Hard copy only.

This paper is part of the following report:

TITLE: Nanostructures: Physics and Technology. 7th International Symposium. St. Petersburg, Russia, June 14-18, 1999 Proceedings

To order the complete compilation report, use: ADA407055

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP012853 thru ADP013001

7th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 14–18, 1999

Electronic structure of stacked self-organized InAs/GaAs quantum dots

P. N. Brunkov†‡, A. Patanè‡, A. Levin‡, A. Polimeni‡, L. Eaves‡, P. C. Main‡, Yu. G. Musikhin†, A. R. Kovsh†, V. M. Ustinov† and S. G. Konnikov†
† Ioffe Physico-Technical Institute, St Petersburg, Russia
‡ School of Physics and Astronomy, University of Nottingham, NG7 2RD Nottingham, UK

Abstract. Capacitance and conductance-voltage characteristics have been measured at various frequencies and temperatures for a Schottky barrier structure containing three sheets of self-organized InAs quantum dots in an n-GaAs matrix. The capacitance of the structure consists of bulk and quantum dot contributions, whereas the conductance mainly depends on the electron transfer out of the dots, which is a function of the balance between measurement frequency and the thermionic emission rate of carriers from quantum dots. An analysis of the temperature-dependent conductance of the structure gives information about the electronic structure and electron emission rate from the quantum dots.

Introduction

In the last few years considerable attention has been given to both experimental and theoretical studies of electronic structure of self-organized quantum dots (QDs) [1-4]. Recently it was shown that when the distance between adjascent QD layers is below 100 Å the vertical alignment of the QDs is observed, resulting in a change in the electronic structure of the stacked QDs [1, 2]. In this paper we provide an analysis of the frequency- and temperature-dependent capacitance (C) and conductance (G) of structures with stacked InAs QDs incorporated in an n-type GaAs matrix. This approach allows us to study the electronic structure and dynamic features of electron trapping into the stacked QDs.

1 Results and discussion

The samples with embedded sheets of self-organized InAs QDs in an n-GaAs matrix, were grown by molecular beam epitaxy on n^+-GaAs (001). The QD section consists of three sheets of InAs QDs with a 50 Å thick GaAs spacer inserted between successive InAs island layers. The QD section was sandwiched between a 0.5 μm-thick GaAs cap and a 1 μm-thick GaAs buffer layer. Both the cap and buffer layers were uniformly doped with Si at 2×10^{16} cm^{-3} except for 100 Å thick undoped spacers on each side of the QD section. Schottky barriers were made by depositing Au through a shadow mask (350 μm diameter). The *C(V)* and *G(V)* characteristics were measured over a frequency range f from 10 kHz to 1 MHz using an HP4275A LCR meter. The amplitude of the measuring signal ($V_{\rm osc}$) was 10 mV.

At 100 K there is a plateau from -2.0 V to -3.6 V in the $C(V)$ characteristic related to the discharging of the QDs (Fig. 1(a)) [4]. For temperatures below 70 K, the plateau in the $C(V)$ characteristic is suppressed and a peak appears in $G(V)$ (Fig. 1). The capacitance is measured by superimposing a small ac signal $V_{\rm osc}$ at a frequency f on the applied dc reverse bias $V_{\rm rev}$. Note that $V_{\rm osc}$ causes a modulation of the charge both at the edge of the space charge region ($dQ_{\rm 3D}$) and at the point where the the bulk chemical potential (μ) in the

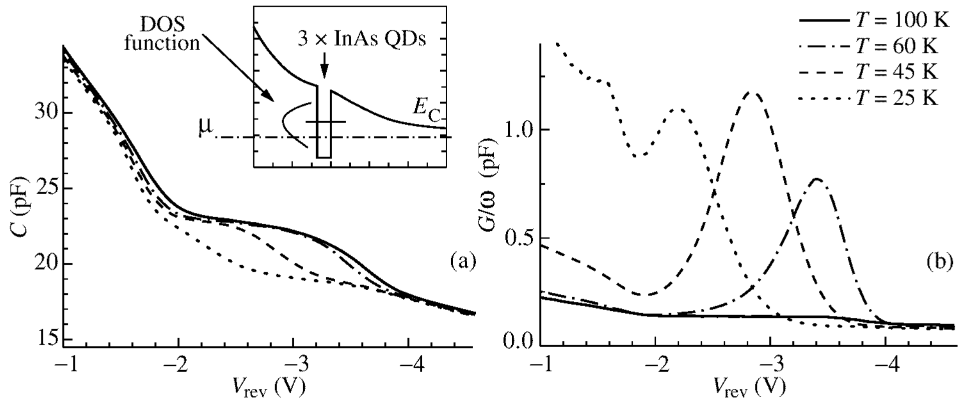

Fig. 1. Temperature dependence of (a) the $C(V)$ and (b) the $G(V)$ characteristics of QD structures measured at $f = 100$ kHz. The insert shows the conduction band diagram of the structure. The horizontal line represents the electron subband energy level E_{qd} in the QDs.

GaAs matrix crosses the density of electron states (DOS) in the QD layer (dQ_{qd}) (inset in Fig. 1).

To reach equilibrium between the QD layer and adjacent GaAs layers, the thermionic emission rate of electrons (e_n) from the QDs must be much higher than $\omega = 2\pi f$. The thermionic emission rate depends exponentially both on the temperature and the energy of the QD electron levels:

$$e_n = e_{n0} \exp \frac{-(E_C - E_{qd})}{kT}, \tag{1}$$

where $E_C - E_{qd}$ is the QD energy level with respect to the bottom of the conduction band and e_{n0} is a characteristic parameter of the QDs.

As the temperature decreases, e_n becomes smaller than ω, i.e. carriers freeze onto the QD levels [4]. This manifests itself as a decrease of the width of the capacitance plateau (Fig. 1(a)) and the appearance of a peak in the *G(V)* characteristics (Fig. 1(b)). G/ω as a function of bias goes through a maximum when $\omega/e_n = 2$ [5]. The conductance peak moves to higher V_{rev} as temperature increases, since the array of QDs has a Gaussian DOS function and deeper (which means lower thermal activation rates) states contribute to the signal at higher V_{rev} (inset in Fig. 1).

The steady state occupation probability of the electron levels in the QDs is determined at a given temperature by the Fermi–Dirac function, depending on the relative positions of the electron level in the QDs (E_{qd}) and the bulk chemical potential μ in the GaAs matrix [4]. The sheet concentration of QDs was found to be $N_{qd} = 5 \times 10^{10}$ cm^{-2} from plan-view transmission electron microscopy. The DOS in the QD sheet may be approximated by a Gaussian function, which describes the spread of energies associated with the distribution of QD sizes [1]. By fitting the *C(V)* characteristic measured at 100 K (Fig. 2(a)) to a quasi-static model [4] we find that the DOS in the QD layer corresponds to a Gaussian distribution with centre at $E_{qd} = 70$ meV from the bottom of the GaAs conduction band and standard deviation of $\Delta E_{qd} = 80$ meV. Calculation of the *C(V)* characteristics of the QD structure shows that the region of quasi-constant capacitance from −2.2 to −3.6 V (Fig. 2(a)) is associated with a decrease in the concentration of electrons in the plane of the quantum dots with increasing reverse bias V_{rev} (Fig. 2(b)). This allows us to estimate

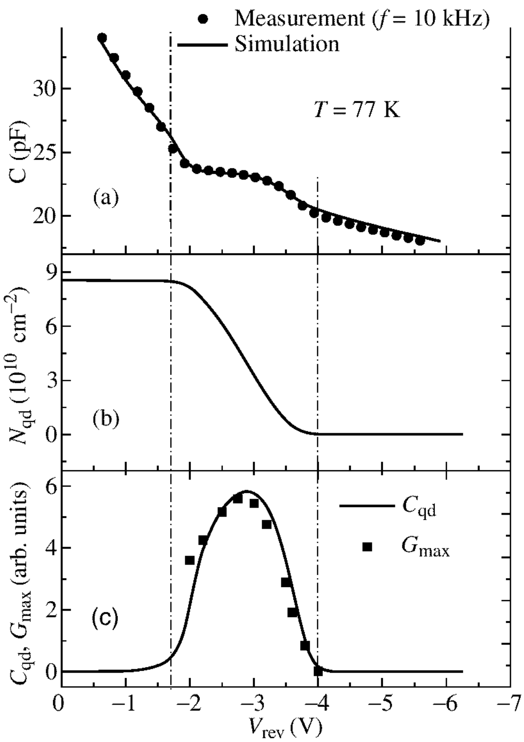

Fig. 2. (a) $C(V)$, (b) $N_{qd}(V)$, and (c) $C_{qd}(V)$ characteristics of the QD structure obtained at $T = 80$ K: experimental data (•) and model calculations (—) for $N_{qd} = 5 \times 10^{10}\,\mathrm{cm}^{-2}$, $E_{qd} = 70$ meV, and $\Delta E_{qd} = 80$ meV.

the capacitance related to QDs as $C_{qd} = qdN_{qd}/dV$ (Fig. 2(c)), where q is the electron charge. From the model it follows that the $C_{qd}(V)$ has a peak at $V_{rev} = -2.8$ V, when the Fermi level crosses the maximum of the DOS in the QD layer.

The thermionic emission rate depends exponentially on both the temperature and the energy of the QD electron levels (Eq. (1)). Therefore, by varying the measurement frequency and the temperature, we can control the C_{qd}. Figure 3 shows (a) $C(T)$ and (b) $G(T)$ characteristics of the QD structure measured at $V_{rev} = -2.8$ V. The temperature at which the feature due to the C_{qd} recovers in Fig. 3(a) depends on the measurement frequency. Each step in capacitance corresponds to a peak in conductance (Fig. 3(a,b)). Fig. 3(c) shows G/T of the QD structure at 100 kHz and at various V_{rev}. As V_{rev} is changed from -1.7 V to -4.0 V the position of the conductance peak moves to higher temperature and the activation energy, Δ_A, determined from the Arrhenius plot (insert to Fig. 3(c)), changes from 12 meV to 61 meV. The amplitude of the conductance peak has a maximum at $V_{rev} = -2.8$ V (Fig. 3(c)), because the conductance is proportional to the $C_{qd}(V)$ (Fig. 2(c)) and therefore reflects the DOS in the QD layer [5].

At $V_{rev} = -2.8$ V, $\Delta_A = 23$ meV, which is 47 meV lower than E_{qd} determined from the quasi-static analysis. The discrepancy may be due to the presence of an excited state between the ground state in the QDs and the bottom of the GaAs conduction band. In addition, there is a high electric field around the QD layer, which results in reduction of the

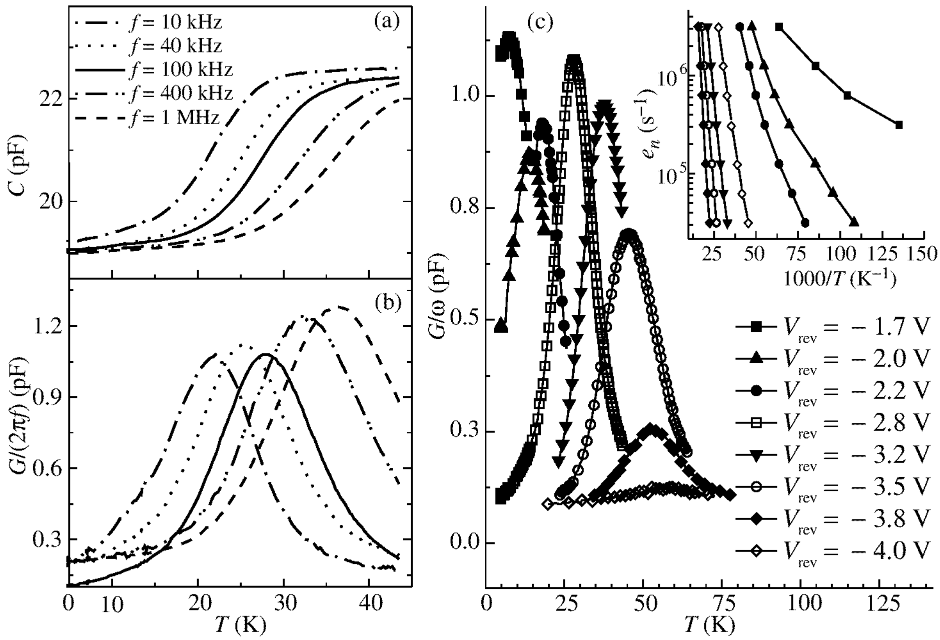

Fig. 3. (a) $C(T)$ and (b) $G(T)$ characteristics of QD structure at $V_{rev} = -2.8$ V. (c) Temperature dependence of conductance measured at 100 kHz as a function of the V_{rev}. Insert shows Arrhenius plot of the emission rates.

activation energy.

2 Conclusions

We have investigated the frequency-dependent admittance spectra of an n-GaAs structure containing self-organized InAs QDs. We find that the the quantum dot contribution to $C(T)$ and $G(T)$ characteristics depends on the relation between the thermionic emission rate e_n of electrons from QDs and the angular measurement frequency ω. Analysis of the admittance spectra provides information about the electron emission rate from the QDs. Since the array of self-organized QDs has a Gaussian DOS, we can study different parts of the QD energy spectrum by changing V_{rev}.

The authors would like to thank EPSRC, Royal Society (UK), and FAPESP (Brazilian Funding Agency) for partial financial support.

References

[1] D. Bimberg, M. Grundmann and N. N. Ledentsov, *Quantum Dot Heterostructures* John Wiley, 1998.

[2] G. S. Solomon, J. A. Trezza, A. F. Marshall and J. S. Harris Jr, *Phys. Rev. Lett.* **76**, 952 (1996).

[3] J. Kim, L.-W. Wang, and A. Zunger, *Phys. Rev. B* **57**, R9408 (1998).

[4] P. N. Brounkov, A. Polimeni, S. T. Stoddart, M. Henini, L. Eaves, P. C. Main, A. R. Kovsh, Yu. G. Musikhin and S. G. Konnikov, *Appl. Phys. Lett.* **73**, 1092 (1998).

[5] E. H. Nicollian and A. Goetzberger, *Bell Sys. Techn. J.* **46**, 1055 (1967).